Measuring imported case risk of COVID-19 from inbound international flights --- A case study on China

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ARTICLE INFO

ABSTRACT

With COVID-19 spreading around the world, many countries are exposed to the imported case risk from inbound international flights. Several governments issued restrictions on inbound flights to mitigate such risk. But with the pandemic controlled in many countries, some decide to reopen the economy by relaxing the international air travel bans. As the virus has still been prevailing in many regions, this relaxation raises the alarm to import overseas cases and results in the revival of local pandemic. This study proposes a risk index to measure one country's imported case risk from inbound international flights. The index combines both daily dynamic international air connectivity data and the updated global COVID-19 data. It can measure the risk at the country, province and even specific route level. The proposed index was applied to China, which is the first country to experience and control COVID-19 pandemic while later becoming exposed to high imported case risk after the epidemic centers switched to Europe and the US afterward. The calculated risk indexes for each Chinese province or region show both spatial and temporal patterns from January to April 2020. It is found that China's strict restriction on inbound flights since March 26 was very effective to cut the imported case risk by half than doing nothing. But the overall index level kept rising because of the deteriorating pandemic conditions around the world. Hong Kong and Taiwan are the regions facing the highest imported case risk due to their superior international air connectivity and looser restriction on inbound flights. Shandong Province had the highest risk in February and early March due to its well-developed air connectivity with South Korea and Japan when the pandemic peaked in these two countries. Since mid-March, the imported case risk from Europe and the US dramatically increased. Last, we discuss policy implications for the relevant stakeholders to use our index to dynamically adjust the international air travel restrictions. This risk index can also be applied to other contexts and countries to relax restrictions on particular low-risk routes while still restricting the high-risk ones. This would balance the essential air travels need and the requirement to minimize the imported case risk.

1. Introduction and background

With the improvement of transportation infrastructure and the reduction in travel cost around the world, international travels, especially by air, have dramatically increased. In 2018, the global air passenger travel has reached 8.3 trillion revenue passenger-kilometers (RPKs) (IATA, 2019). The global RPKs have kept an average annual 6% growth since 2010. Thanks to the globalization and increasing liberalization of bilateral air service agreements (ASAs), the international airline network and air passenger have been expanded dramatically (Winston and Yan, 2015; Oum et al., 2019). China and other Asia Pacific

regions lead the air travel increase in the world (Wang et al., 2018). China has been the world's second largest airline market since 2005 (Fu et al., 2015). In 2018, the market served 1.27 billion passenger travels, with 60 airlines, 3639 transport aircraft, 4945 regular flight routes, 230 domestic cities with regular flights (excluding Hong Kong, Macao, and Taiwan), operating flights to 165 cities in 65 countries (Civil Aviation Administration of China (CAAC), 2018). Such domestic and international air connectivity allows people to travel around the world easily, stimulating trade and people-to-people exchanges. But it may also facilitate infectious disease to spread rapidly around the world. International air travel has acted as important media to contribute to fast

spread of several pandemics in the past, for example the SARS in 2013 and H1N1 in 2009 (Wilder-Smith et al., 2003; Browne et al., 2016; Cai et al., 2019).

The first COVID-19 case was recorded in Wuhan China on December 9, 2019 (Huang et al., 2020) . The virus then quickly spread to the rest of China in January, and then the rest of world has started to report an increasing number of cases. On January 30, 2020, the World Health Organization (WHO) classified COVID-19 as a Public Emergency of International Concern (PEIC). On March 11, 2020, Dr. Ghebreyesus, the Director of WHO, announced that the COVID-19 has constituted a global pandemic. As of July 20, 2020, there were over 14.5 million confirmed cases in 188 countries and regions (JHU CSSE, 2020).

Since there have been no effective drugs or vaccines available, restricting cross-border people flow and imposing strict social distance requirement or quarantine rules are the only ways to contain COVID-19 spread domestically and globally (Oum and Wang, 2020). For example, China has quickly locked down Wuhan and the surrounding regions since January 23, suspending all intra-city public transit, and blocked all inter-city and international travels between Wuhan and other regions. Other Chinese cities also responded actively, banning inter-provincial travels and cutting inbound flights. With many earliest overseas confirmed cases reporting Wuhan travel history, China and other countries greatly reduced international flights to China and imposed strict inspections on Chinese flights. Many airlines also voluntarily canceled most of their flights with China even before their governments formally responded to mitigate virus spread risk, including British Airways, Lufthansa, Air Canada, etc.[1]

Thanks to the government's strict quarantine and case tracing measures, the pandemic in China has been controlled since early March. The hospitalized cases have dropped from 58,090 in mid-February to less than 20,000 at the end of March. On April 8, 2020, Wuhan reopened after more than 10 weeks in lockdown. Air and train services have resumed. However, COVID-19 has quickly spread globally, leading to a serious pandemic in Europe and then North America. The epidemic centers are thus switched from China to these two regions, which in turn makes China to be exposed to high imported case risk via its international air connectivity. In particular, China reported more than 300 imported cases from other countries, with about 100 cases confirmed at Beijing airport, where the largest amount of direct overseas flights operated. Thus, to minimize such imported case risk, since March 29, CAAC has promulgated the "one-airline, one-country, one-flight-per-week policy" (CAAC, 2020). That is, only one airline from China or the foreign country is allowed to operate the route between two countries; One route can only have only one flight per week; China only maintains direct flights to one destination of each foreign country. In addition, CAAC launched a comprehensive inspection and quarantine procedure for the inbound airline passengers.

Now, many countries consider reopening the economy and relaxing the international travel ban. For example, more than forty states in the US decided to open up in May and several European countries designed multiple-phase reopening plans, which have been implemented since early May. However, the pandemic has not been well controlled in many countries, such that the aggressive relaxation of international air travels restrictions would inevitably bring about high imported case risk to other countries. This could result in a revival of pandemic in many places where the COVID-19 spread has been initially controlled. Thus, before fully removing the international air travel ban, it is important for the government to comprehensively evaluate the imported case risk, and design corresponding control measures on inbound flights.

This study thus aims to propose an index to evaluate the imported case risk of COVID-19 through international air travel. Specifically, we use the Chinese data to construct such an index in order to measure the imported case risk faced by each Chinese province. The index explicitly accounts for the international air connectivity between China and the foreign countries, and also the detailed pandemic data in each foreign country. The risk index is calculated for each Chinese province on a daily basis from January 1 to April 16, 2020. Both the spatial and temporal patterns of the imported case risk can be examined in detail. Moreover, we can also evaluate how such risk is affected by the government's restriction on international air travel and the dynamic change in global pandemic development in each foreign country.

Such a risk index has important policy implications. The policymaker can apply this index to dynamically monitor and adjust its air travel restrictions with each foreign country. For example, they can consider relaxing the air travel restriction and resuming air connectivity with those low imported risk regions, but probably further tightening or lengthening the duration of the restrictions with those high imported risk regions. With more and more countries succeeding in controlling the domestic pandemic, such imported case risk index can be applied in more contexts to provide in-advance alert and also suggest a more effective strategy to gradually lift international air travel bans, while minimizing the imported case risk and resultant pandemic revival.

The paper is organized as follows. Section 2 reviews the related recent studies on the interrelationship between international air travel and COVID-19 global spread. In Section 3, we combine the real-time data of global flights with the dynamic global COVID-19 pandemic data to construct an index measuring imported case risk for each country with which China has air connection. Section 4 discusses the results of the index calculation and tries to distinguish the patterns from temporal, spatial, source, and route distribution perspectives, respectively. The policy implications are also discussed in this section. Section 5 concludes this study.

2. Review of related recent studies

Since China's COVID-19 pandemic started in January, many scholars around the world modeled and predicted its transmission path and growth trajectory. In particular, people flow plays an essential role in the fast spread of COVID-19. For example, Tang et al. (2020) calibrated a random transmission model of COVID-19 to predict the virus spread within China by using the people outflow from Wuhan to different parts of China by different transport modes, such as airlines, rail, and coaches. Lau et al. (2020) evaluated the effect lockdown of Wuhan and the air travel ban to contain China's domestic pandemic. They found the air travel ban has greatly helped slow the COVID-19 spread in China. Zhang et al. (2020) compared the effect of different transport modes on COVID-19 spread in China. They found that air transport is more closely associated with the virus spread than high-speed train.

Later on, more attention has been paid on the global spread via international travels, especially air travel. Gilbert et al. (2020) quantified the importation risk of COVID-19 faced by African countries by examining its international connectivity with China. They suggested that particular African countries were vulnerable and should be prepared. However, this study only considered the flights with China, ignoring the potential imported case risk from Europe and North America. Since mid-March, these regions have already surpassed China in both confirmed cases and death tolls. Boldog et al. (2020) combined the cumulative number of cases in China and the average connectivity with China to estimate the risk of pandemic outside China. It also proposed that the most effective control measure to reduce imported case risk is through strict entry screening and restrictions on international air travel.

Matteo Chinazzi et al. (2020) applied a global population transmission model to predict the impact of Wuhan lockdown to contain the virus spread. They pointed out the lockdown only delayed pandemic progression by 3–5 days within China, while the international travel restrictions are more effective to help slow spread from China to the rest

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[1] Please see the following links for information: https://www.businessinsider.com/airlines-canceling-changing-flights-to-china-amid-coronavirus-fears-2020-1.

Table 1
Notation glossary.

	Variable/ index	Definition
Space and Time	n	n-th day
	i	foreign region
	x	import region
COVID-19 cases	A_i^n	total number of COVID-19 cases on the n-th day
	Ac_i^n	confirmed cases one day the before the n-th day
	Aq_i^n	correction term measuring the potential new cases
	Am_i^n	imported cases for region i from other countries
	F_i^n	new confirmed cases on the n-th day
	Q_x^n	potentially infected population in region x on the n-th day
	S_x	population of region x
Air traffic parameter	$connectivity_{x,i}^n$	international air connectivity between region x and i
Risk index	M_j^n	imported case risk index
	$\overline{M}_j^n$	relative risk index

of the world until mid-February. The immediate reduction in international fights between China and other countries has indeed slowed down the global pandemic in February and March.

Without available real-time flight data, Tuite et al. (2020) used the flight data published by IATA in 2015 to study the rapid COVID-19 spread in Italy due to the imported cases from China. The empirical results and prediction, however, might be inaccurate in that the flight schedules could have dramatically changed since 2015, especially after many international flights had been canceled amid the pandemic. In addition, Acuna-Zegarra et al. (2020) studied the COVID-19 spread in Mexico and Latin America. International air travel and the associated imported case are found to contribute to the rapid spread in this region. Nikolaou and Dimitriou (2020) analyzed the topology of the global airport network to provide evidence about the possible transmission of infectious diseases in Europe through the airline system.

Most of the abovementioned studies are to examine how air transport facilitates COVID-19 spread domestically and globally. However, few

studies are concerned about how to accurately measure and control the imported case risk due to international air travel. With more countries having controlled the domestic community spread, their focuses have now turned to prevent the imported cases. It is thus essential to evaluate the imported case risk. If the country resumes air connectivity with the high-risk partners too early, there is a high chance of the pandemic revival because of the imported cases. In addition, few studies used the real-time flight dynamics data for COVID-19 spread analysis, such that their analysis is not dynamically updated. To address this issue, this study utilizes a large dataset including all the Chinese international flight real-time information, which can measure the imported case risk from international air travel, providing in-time suggestions to policy makers to adjust the air travel restrictions.

3. Methodology and data

3.1. Imported case risk index

This section develops the index to measure the imported case risk through international air travel for one region. We apply this index onto different Chinese regions, including 31 provinces, Hong Kong, Macao, and Taiwan regions (hereafter, "province" is used to refer to each Chinese region). Specifically, the imported case risk from one particular foreign country should be positively correlated to the real-time bilateral air connectivity and also the pandemic situation of this foreign country. Our index thus explicitly accounts for both the air connectivity and also the severity of pandemic of the foreign country. Table 1 collates the notation glossary used in our calculation methods.

The superscripts $1, 2, \ldots, n-1, n$ indicate the days. The total number of confirmed COVID-19 cases in the foreign region i is denoted as A_i^n. It includes the number of confirmed cases Ac_i^n one day before day n (such data is released with one-day lag); a correction term Aq_i^n to measure the potential new cases on day n; the estimated number of imported cases for region i from other countries Am_i^n. The number of cases A_i^n is the sum of three terms Ac_i^n, Aq_i^n and Am_i^n, which is expressed as Eq. (1).

$$A_i^n = Ac_i^n + Aq_i^n + Am_i^n \tag{1}$$

In order to estimate the new cases on day n, namely Aq_i^n, we use the confirmed new cases in previous days. This is achieved by solving the following ordinary differential dynamical system.
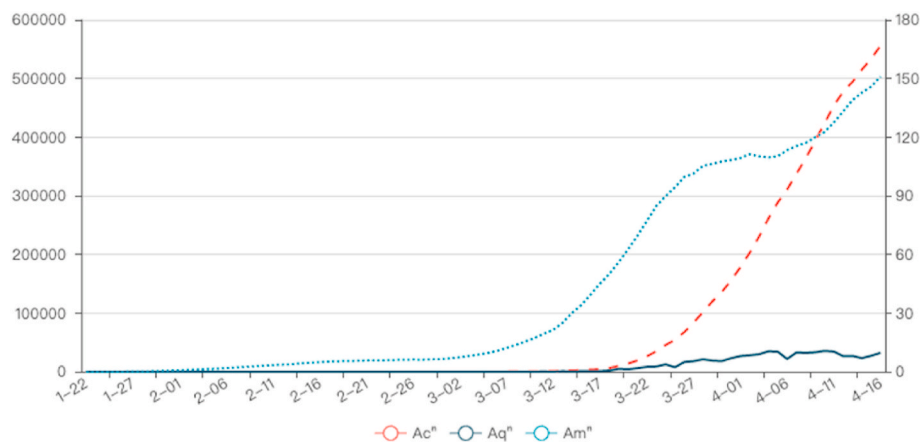

Fig. 1. Evolution of Ac_i^n, Aq_i^n and Am_i^n of the US.

$$\frac{d}{dt}y(t) = F(t) \tag{2}$$

To solve for the above ordinary differential dynamical system, we need to give an explicit and multi-step discrete numerical scheme. We select a two-step eccentric scheme, called Admas-Bashforth scheme (Beeman, 1976), This method is widely used in disease spread, physics, and biology research to make correction of the time-series changes for one variable (Xiao et al., 2009; Khan et al., 2019; Kumar et al., 2020).

$$y((n+1)\Delta t) = y(n\Delta t) + \frac{\Delta t}{2}(3F(n\Delta t) - F((n-1)\Delta t)) \tag{3}$$

where Δt is the time difference, which is defined as one day in our model. This leads to the following expression of Aq_i^n as Eq. (4).

$$Aq_i^n = \frac{1}{2}(3F_i^n - F_i^{n-1}) \tag{4}$$

where F_i^n and F_i^{n-1} are the numbers of new confirmed cases on days n and $n-1$ of the region i.

As most of the countries in the world do not report the imported cases or they are unable to trace such cases accurately, we adopt the following approach to estimate the number of imported cases of the region i, which is Am_i^n, by Eq. (5).

$$Am_i^n = \sum_{k=1}^{13} \sum_x Q_x^{n-k} connectivity_{x,i}^{n-k} \tag{5}$$

and

$$Q_x^{n-k} = \frac{A_x^{n-k}}{S_x} \tag{6}$$

Q_x^{n-k} is the share of the potentially infected population in region x on day $n-k$, where A_x^{n-k} is the total number of potential cases in region x on day $n-k$ and S_x is the population of region x. Thus, the accumulated number of imported cases for region i (i.e., Am_i^n) can be calculated using Eq. (5), which multiplies Q_x^{n-k} with the bilateral air connectivity. The variable $connectivity_{x,i}^{n-k}$ is to measure the international air connectivity between region x and i. Such an air connectivity index is calculated using the method proposed in Zhu et al. (2018). This connectivity measurement not only accounts for the number of flight frequency and seats, but also considers the service quality factors, such as the flying distance and number of transfers (Zhang et al., 2017).

Taking the US as an example, we exhibit its evolution of Ac_i^n, Aq_i^n, and Am_i^n in Fig. 1. It can be seen that, although the COVID-19 pandemic in the US only started from mid-March as suggested by the trend of Ac_i^n, the imported case risk has already risen dramatically since February as suggested by Am_i^n. This is because the US had maintained most of its international flights with the rest of the world. Although the US has banned international flights from China since early February, it has kept most of the flights from the European countries where COVID-19 has already widely spread in February and most of the March. After the US further decided to restrict travels with Europe from mid-March, its imported case risk became flattened.[2] The transmission within local communities became the dominant source of the confirmed cases afterward. The number of imported cases and the associated risk increased again since mid-April because of the deteriorating pandemic conditions in more regions around the world with air connection to the US. A similar analysis can also be conducted for other countries by disentangling the trends of Ac_i^n, Aq_i^n and Am_i^n.

Similar to Eq. (6), we can define the share of the potentially infected population for each region i on day n, which is expressed in Eq. (7).

$$Q_i^n = \frac{A_i^n}{S_i} \tag{7}$$

Then for each Chinese province indexed by j, we are able to define its imported case risk on day n as follows,

$$M_j^n = \sum_i Q_i^n connectivity_{i,j}^n \tag{8}$$

where $connectivity_{i,j}^n$ is the air connectivity between Chinese province j and foreign country i on day n.

The proposed imported case risk index M_j^n involves several assumptions to simplify calculation and to generate clearer implications. First, to measure the share of infected population in foreign regions, namely the variable Q_i^n, we treat most of the foreign countries as a whole, not distinguishing the different provinces/states/cities (airports) within that country i. This is mainly due to the unavailability of the detailed pandemic data at the more specific province/state/city level for most countries, including Russia, Canada and the European countries. But, as will be discussed later, the US has maintained very detailed pandemic data available at the state level, such that we are able to evaluate the imported case risk from each individual US state. With daily more than fifty thousand new confirmed cases reported each day since July, the US has accumulated more than 3.5 million cases, suffering the most severe pandemic in the world. The pandemic conditions also vary significantly among different states over time. The number of confirmed cases for particular US states, such as New York, Florida and California, can far exceed that of an entire country in Europe and Asia. Thus, it is meaningful and necessary to distinguish different states when measuring their imposed risk to China. Second, due to data availability, when calculating the air connectivity, we use the number of available seats to measure the air travel capacity, instead of the actual passenger traffic number. To control in-vehicle transmission risk, governments and airlines impose strict rules to control the load factor of the international flights, and a widely adopted policy is to leave one empty seat between two passengers. Therefore, using the scheduled seats might exaggerate the air connectivity. But as almost all the airlines adopt the same principle, it would not change the relative level of imported risk from different countries when compared among regions. Third, the index M_j^n accounts for the first entry point of the international flights. Since late March, China diverted many international flights from Beijing, Shanghai and Guangzhou to other secondary airports in Xi'an, Shenyang, Shijiazhuang, Tianjin, etc. This is to alleviate the huge workload of the gateway airports after strict inspection and quarantine policies have been implemented upon the inbound flights and passengers.[3] Last, our index does not consider the effect of strict quarantine and inspection adopted on inbound flights. The index only measures the potential imported case risk brought by the international air connectivity from foreign countries with the pandemic. Instead, the index can help policy makers adjust the strictness to inspect the inbound flights for provinces with different risk levels.

The absolute value of the index M_j^n does not have a specific meaning, while it is intuitive that a higher value of M_j^n indicates a higher imported case risk for province j in China. As an alternative, we normalize M_j^n into a relative risk index as below,

$$\overline{M}_j^n = \frac{M_j^n}{M_0} \tag{9}$$

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[2] See the BBC news about the US ban on European travels: https://www.bbc.com/news/world-us-canada-51883728.

[3] All inbound airline passengers were asked to conduct nucleic acid testing and undergo 14-day quarantine since March 24. Such policy overwhelmed major Chinese airports, including Beijing, Shanghai and Guangzhou. Then, since March 29, CAAC has assigned many international flights to change their landing airport from Beijing, Shanghai and Guangzhou to other secondary airports with capacity to fulfill the strict inspection rules.
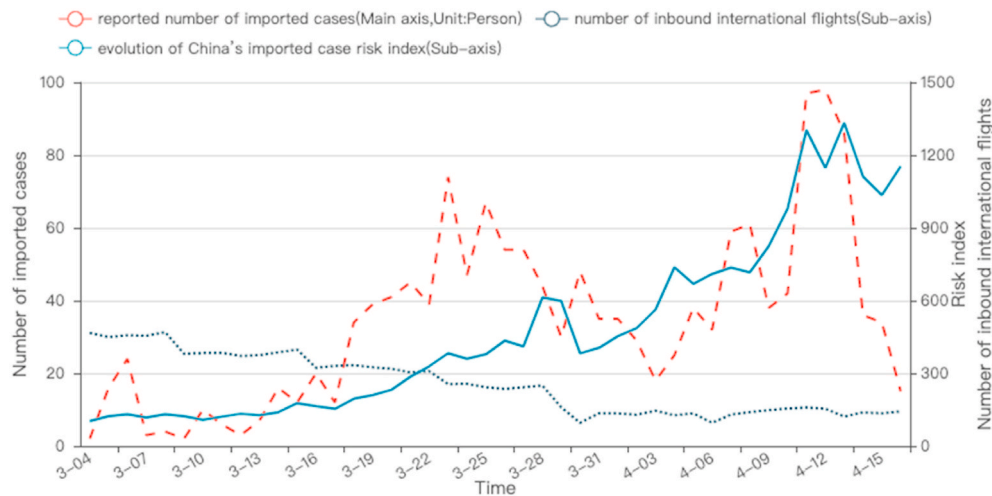
Fig. 2. Evolution of China's imported case risk index, reported number of imported cases and the number of inbound international flights.

M_0 is the benchmark risk level. Here, the import risk level of Shanghai on February 2 is used as the value of M_0. Thus, all the values and evolutions of M_j^m can be demonstrated more easily.

3.2. Data

Our data involves both the dynamic real-time international flight information and the COVID-19 pandemic data around the world. The international flight data is was obtained from UMETRIP to calculate the air connectivity.[4] UMETRIP is the largest aviation data service company in China, which is jointly operated by China TravelSky Holding Company Limited and TravelSky Mobile Technology Limited. Both are state-owned companies to operate the air ticket booking and integrated with IATA's global air ticket reservation system. UMTRIP provides flight information of more than 50 million air passengers per day in the world. We collected flight information for all the international air service since January 1, 2020, including the flight number, the operating airline, origin and destination, transferring airport, number of scheduled seats, aircraft type, scheduled departing and arriving time, etc.

For the COVID-19 pandemic data, we refer to the database maintained by the Center of Systems Science and Engineering at Johns Hopkins University (Dong et al., 2020; JHU CSSE, 2020). The COVID-19 data reported by JHU CSSE is integrated from various reliable data sources, including the World Health Organization (WHO), the United States Centers for Disease Control (US CDC), the European Centers for Disease Control (European CDC), the worldometers. info website, BNO news agency, and the CDCs of various countries and regions. Finally, the world population data is collected from the World Bank database.[5] But the statistical scope could vary from country to country. For example, for China and US, the COVID-19 pandemic data can be subdivided into each province or state. Therefore, we are able to measure the imported case risk from each individual US state on each Chinese province. However, such data of most other countries are only available at the country level.

4. Results and discussions

This section presents our calculated imported case risk indexes for China and its different provinces. The evolution of risk patterns is also

discussed with the policy implications suggested. Specifically, this section includes the following four parts. First, we examine the evolution of China's overall imported case risk. Second, the imported case risk for each province is demonstrated and ranked. Third, we further identify specific foreign countries that impose the highest imported case risk for each Chinese province. Finally, we investigate the imported case risk on different major Chinese international routes. This would provide more specific policy implications for the Chinese government to dynamically adjust the international travel restrictions for individual routes or airlines.

4.1. Overall imported case risk for China

First, China's overall imported case risk can be obtained by aggregating the risk index of each Chinese province (i.e., Eq. (8)). This overall risk index is shown in Fig. 2, together with the daily number of inbound international flights and the reported daily imported cases. With the COVID-19 spreading around the world, China's imported case risk index and the reported imported cases show a rising trend. The pattern of the risk index is almost consistent with the actual number of reported imported cases. However, in mid-March, the reported imported case increased faster than the risk index. This is probably because, at the early stage of the global spread of COVID-19, many overseas infected Chinese were eager to return China to get treatment when China has almost controlled the pandemic and the medical system has been more experienced in curing the disease. Our risk index is to reflect the potential imported case referring to the average population, thus underestimating the actual imported cases. But China has cut the inbound international flights since the end of March, especially launching the "one-airline, one-country, one-flight-per-week policy". This effectively reduced the number of reported imported cases and the risk index. When the overseas Chinese return travels were discouraged and the foreign countries' medical systems got more capable to treat the patients, the infected overseas Chinese were not desperate to fly back to China. Thus, our risk index is more useful to measure the overall imported case risk as it represents the average population of the foreign country. In addition, it is also observed that, since the end of March, our risk index leads the reported imported cases by about 5–7 days, which is almost consistent with the average latent period of COVID-19. Thus, our risk index can provide in-advance alert and information update to policy makers to adjust international air travel policies in a timely manner.

Despite the cut of inbound flights, China's overall imported case risk index still rose in April, attributable to the much deteriorating COVID-19
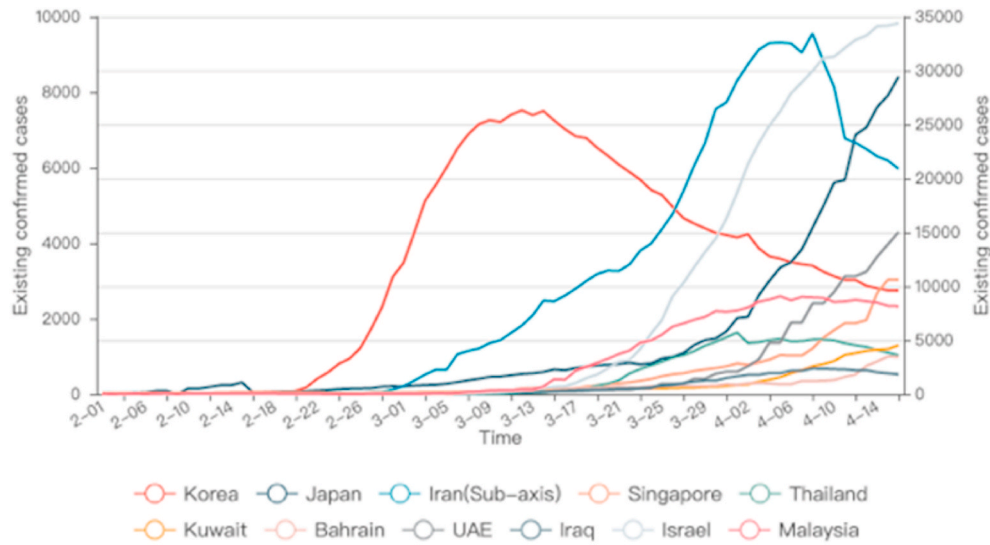
(a). Asia
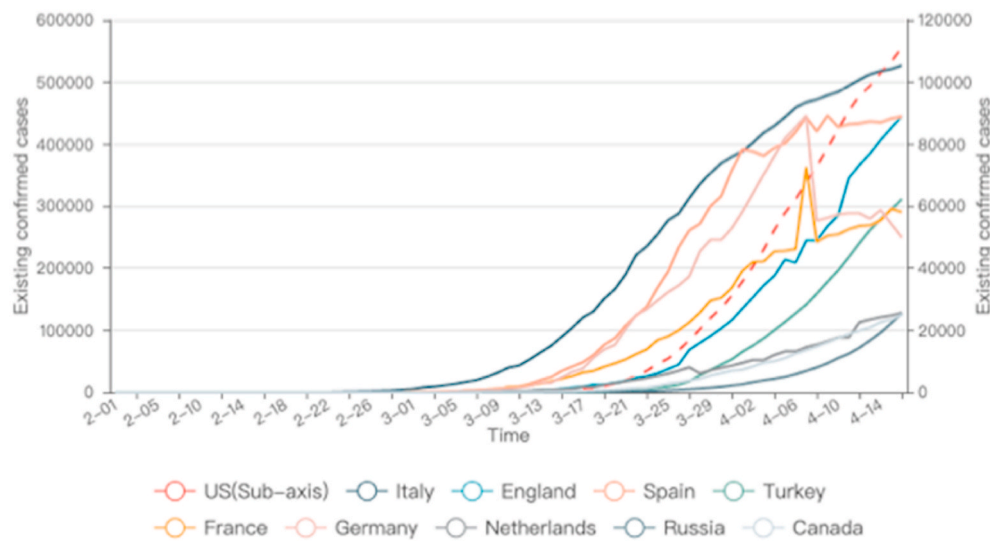
(b). North America and Europe

Fig. 3. The number of existing confirmed cases in major regions around the world. Note: we use the different y (vertical)-axis (on the right-hand side) for Iran and the US in Fig. 3(a) and (b) respectively, as these two countries experienced much faster confirmed cases growth than other countries. Such treatment makes the figures to exhibit more clearly.
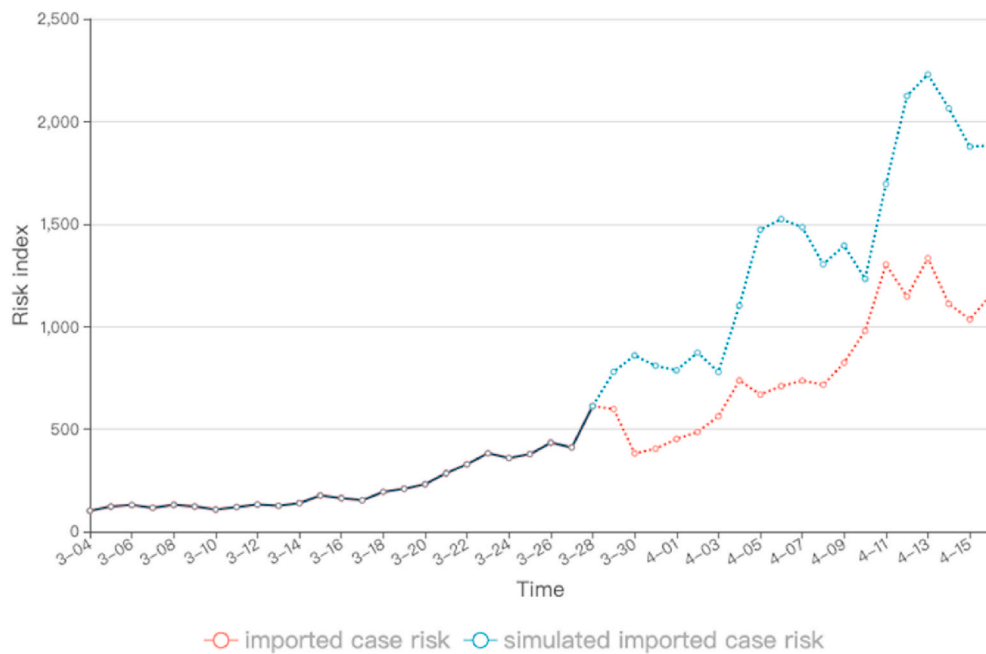
Fig. 4. The comparison of China's overall imported case risk with and without the inbound flight cut policy.

Table 2
Ranking of imported case risk in February 2020.

Date	February 2		February 12		February 22	
Ranking	Province	Risk Index	Province	Risk Index	Province	Risk Index
1	Hong Kong	2.753	Taiwan	8.566	Taiwan	13.491
2	Taiwan	1.851	Hong Kong	6.58	Hong Kong	5.653
3	Shanghai	1.000	Shanghai	2.54	Shandong	3.281
4	Beijing	0.756	Beijing	1.049	Shanghai	2.698
5	Guangdong	0.517	Guangdong	0.435	Beijing	1.839
6	Shandong	0.367	Sichuan	0.348	Liaoning	0.936
7	Fujian	0.299	Liaoning	0.301	Heilongjiang	0.881
8	Liaoning	0.22	Shandong	0.214	Jilin	0.836
9	Jiangsu	0.199	Jiangsu	0.195	Tianjin	0.61
10	Sichuan	0.196	Macao	0.185	Jiangsu	0.588

spread around the world. As can be seen in Fig. 3, COVID-19 first spread to Asian countries due to their geographic proximity and more frequent people flow with China. Then the pandemic has been well controlled in these Asian countries by mid-April, thanks to their governments' fast response and powerful measures. However, confirmed cases in Europe and the US have grown exponentially since mid-March. This makes these two regions to become the new global pandemic centers, thus imposing considerable imported case risk to China and other countries.

China's policy to cut inbound flights at the end of March could be quite effective to control the imported case risk when the pandemic center switched to Europe and the US. To better evaluate the policy effect, a counterfactual analysis is done to simulate China's imported case risk when assuming no international travel restriction was taken in China. Fig. 4 shows the simulated risk index in the green color, which far exceeds our risk index with the policy implemented. This empirical evidence clearly demonstrates the effectiveness and importance to restrict the inbound flight on controlling the imported case risk.

4.2. Imported case risk for each Chinese province

This section reports the evolution of each Chinese province's imported case risk by its international air connectivity. Different Chinese provinces have quite distinct international connectivity patterns in terms of the number of flight frequencies and distribution of foreign

destinations. The calculated risk indexes are ranked among the riskiest provinces in February, March and April, respectively. These results are collated in Tables 2–4. Our benchmark is set as the risk level of Shanghai as of February 2.[6] Thus, all the index numbers can be interpreted as the relative risk compared to that of Shanghai on February 2.

First, the risk indexes of major provinces were still very low in February. Although the international flights were still operated as normal, the pandemic was still contained within China. Thus, there was little risk of imported cases from overseas. On February 2, Hong Kong's risk index was 2.753 times of Shanghai, while Jiangsu's risk index was only one-fifth of Shanghai. Ten days later (February 12), Shanghai's risk index increased to 2.54, and the risk of other regions also generally rose.

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[6] Shanghai is selected as the baseline as it is the most economically developed city in China, and it is also the most connected Chinese city with the world by air and maritime transport. Shanghai also has the fastest and most frequent update on daily COVID-19 pandemic development in China. The accuracy and reliability of its released data could be the highest in China. In addition, February 2 is selected is because the first confirmed case in Shanghai was reported on January 20 (Yao, 2020). The latent period for COVID-19 can be as long as two-week (14 days). Thus, the transmission and outbreak caused by the first reported case can start as late as February 2. We therefore use February 2 as the remarking date for Shanghai to face the real challenge of COVID-19 outbreak.

Table 3
Ranking of imported case risk in March 2020.

Date	March 2		March 12		March 22	
Ranking	Province	Risk Index	Province	Risk Index	Province	Risk Index
1	Shandong	30.448	Hong Kong	27.837	Hong Kong	93.438
2	Shanghai	24.502	Taiwan	20.736	Taiwan	69.212
3	Beijing	10.872	Shanghai	16.389	Shanghai	60.372
4	Taiwan	10.147	Beijing	15.804	Beijing	43.781
5	Guangdong	8.895	Shandong	14.941	Guangdong	42.553
6	Hong Kong	7.305	Liaoning	9.045	Shandong	11.345
7	Liaoning	6.339	Guangdong	8.868	Tianjin	8.545
8	Jilin	6.177	Tianjin	5.962	Fujian	7.969
9	Tianjin	4.163	Shaanxi	5.867	Liaoning	7.461
10	Jiangsu	4.125	Jilin	5.867	Jilin	4.402

Table 4
Ranking of imported case risk in April 2020.

Date	April 2		April 12		April 16	
Ranking	Province	Risk Index	Province	Risk Index	Province	Risk Index
1	Shanghai	200.705	Shanghai	253.347	Taiwan	351.8334
2	Beijing	136.604	Hong Kong	228.784	Hong Kong	303.8061
3	Hongkong	103.1869	Taiwan	127.337	Shanghai	314.1463
4	Taiwan	91.7039	Guangdong	91.932	Beijing	57.1159
5	Guangdong	25.4891	Sichuan	53.856	Guangdong	49.4020
6	Tianjin	22.7130	Fujian	27.795	Sichuan	43.5387
7	Shandong	14.8031	Beijign	22.523	Zhejiang	38.3895
8	Shaanxi	7.1118	Macao	21.787	Tianjin	19.5228
9	Fujian	4.9758	Shandong	3.212	Shaanxi	16.9699
10	Sichuan	3.5822	Liaoning	2.577	Fujian	9.2334

Hong Kong and Taiwan were ranked the riskiest, because of their far more advanced international air connectivity with the rest of the world. It is also noted that by February 22, Shandong's risk index suddenly and dramatically rose, replacing Shanghai as the riskiest province in mainland China exposed. This was mainly because COVID-19 started to outbreak in South Korea since mid-February. There were a large number of flights between Shandong and South Korea. Shandong had South Korea as the largest FDI sourcing country, and millions of South Korean reside in Shandong. China also signed an open-skies agreement with South Korea to free Shandong for flight operations, which further boosted the air connectivity between Shandong and South Korea (Liu and Oum, 2018).

In March, the magnitudes of the risk index of all the provinces started to explode. The riskiest provinces had seen ten times growth in the risk index in early and mid-March when compared to that of February. In terms of the ranking, Shandong became the riskiest province in China on March 2, even surpassing Taiwan and Hong Kong. This is because the pandemic in South Korea deteriorated (see Fig. 3) fast in early March, while the flights between Shandong and South Korea had yet been reduced accordingly. The risk index of Taiwan and Hong Kong declined slightly in early March, while returned to the top of the ranking since mid and late of March. Beijing and Shanghai's risk indexes also rose slightly in mid-March. Shandong's risk index fell since mid-March when the pandemic in South Korea was controlled and the inbound flights were cut as well. On March 22, Hong Kong, Shanghai, Taiwan, Beijing and Guangdong all experienced a significant increase in the risk index. This was due to their well-developed air connectivity with the US and Europe where the pandemic explored since late March. In view of such serious imported case risk, on March 29, CAAC finally decided to implement the tough flight cut policy, the so-called "one-airline, one-

country, one-flight-per-week policy".

In April, the risk index of Hong Kong and Taiwan still kept rising, ranked at the top among all Chinese regions. Although CAAC has adopted an effective inbound flight cut in mainland China, Hong Kong and Taiwan had yet adopted powerful measures to reduce their international flights. For Shanghai, its risk index was also very high, because it has the most developed international air connectivity among Chinese provinces. Shanghai still serves as the important international hub airport to maintain China's essential air travel with the rest of the world.

To better illustrate the spatial and temporal changes of the imported case risk for each Chinese province, we further draw Figs. 5–7 to visualize each province's risk index in February, March and April, respectively. The risk indexes range from value 0 to 352. The smaller the value, the bluer the color in the figure; the larger the value, the redder the color in the figure. It can be seen that the risk indexes of all Chinese regions were relatively low in February. In March, the risk index in Beijing, Shandong, Guangdong, Hong Kong and Taiwan rose. In April, with CAAC's policy to cut inbound flight, Shandong's risk index became lower, while Guangdong, Taiwan, Hong Kong, Beijing, and Shanghai were facing more imported case risk due to deteriorating pandemic in Europe and the US.

4.3. Imported case risk from different foreign countries

In this section, we further identify the major foreign countries (for the US, the scope is the individual state) which impose the imported case risk to each Chinese province. Such analysis could provide more direct implications for policy makers to tailor its flight restrictions targeted to different foreign countries. As China's imported case risk was low in February, our analysis is thus conducted for March and April. Table 5

Fig. 5. Visualization of each province's risk index in February 2020.

exhibits the main foreign countries or US states that impose the imported case risk for the five riskiest Chinese provinces in March and April.

In early and mid-March, China was mainly exposed to the imported case risk from several Asian countries, especially South Korea and Japan. South Korea had the largest number of confirmed cases outside China in early March. In late March, Europe and the US turned into pandemic centers in the world, thus becoming the major source of imported case risk to China. For the imported risk from the US, it can be seen that New York state imposed the highest risk to Chinese provinces and regions since late March. This is sensible as New York was the first state to occur the large-scale outbreak in the US, while China had not entirely cut direct flights with New York.[7] Then, later, with the pandemic spreading to more US states, it is noted that California, Illinois, Alaska, and Washington began to impose very high imported case risk on Chinese provinces because China kept some direct flights with these states. As the two largest economies in the world, the US and China have very strong economic ties and huge bilateral international air travel demand. China's current tight restriction on international flights

dramatically cut air service supply between China and the US, pushing up the ticket price. As a result, the US airlines are also eager to resume the service to China, especially when the Trump administration always encouraged each state to reopen the economy. However, given the deteriorating pandemic condition in the US, China has not significantly relaxed the international flight restriction with the US.[8] This can be justified by the current very high imported case risk of New York, California, Illinois, and Washington imposed on China. Once the restrictions are lifted at the current situation, such imported risk could explode, which cannot be easily handled by the Chinese government.

As shown in our previous section, the risk indexes of Hong Kong, Beijing, and Shanghai are highly correlated to the pandemic development in Europe and the US. Fig. 8 shows the evolution of daily confirmed cases of major pandemic countries, including South Korea, Japan, Singapore, Spain, the US, Italy and Russia. It can be seen that the number of confirmed cases in each foreign country explains their imported case risk imposed on Chinese different provinces.

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[7] From Table 5, we see New York did not impose imported case risk for some particular dates (e.g., April 12), simply because China has cut flights with New York and there was no flight on that particular day.

[8] The Trump administration threatened China to ban all Chinese airlines to fly to the US if China does not relax its restriction on US airlines (see https://www.cbc.ca/news/business/reuters-trump-china-1.5596578). China then partially relaxed the ban and allowed some US airlines to resume service since late June.

Fig. 6. Visualization of each province's risk index in March 2020.

Fig. 7. Visualization of each province's risk index in April 2020.

Table 5
Major countries to impose the risk for the top riskiest Chinese provinces.

Date	Risk	Province	Foreign Countries
March 2	30.448	Shandong	Korea, Canada, Malaysia
	24.502	Shanghai	Korea, Japan, Iran
	10.872	Beijing	Korea, Japan, Singapore
	10.147	Taiwan	Korea, Japan, Singapore
	8.895	Guangdong	Korea, Singapore, Japan
March 12	27.837	Hong Kong	Qatar, Korea, Singapore
	20.736	Taiwan	Korea, Singapore, Japan
	16.389	Shanghai	Korea, Qatar, Singapore
	15.804	Beijing	Korea, Spain, Germany
	14.941	Shandong	Korea, Malaysia, Japan
March 22	93.4379	Hong Kong	Italy, Germany, Qatar
	69.3124	Taiwan	US-NY, Germany, US-WA
	60.3724	Shanghai	Korea, Germany, Belgium
	43.7813	Beijing	US-NY, Germany, Korea
	42.5536	Guangdong	US-NY, Belgium, Qatar
April 2	200.7058	Shanghai	US-NY, Germany, UK
	136.6038	Beijing	US-NY, Germany, UK
	103.1869	Hongkong	UK, Netherlands, Australia
	91.7039	Taiwan	UK, US-WA, France
	25.4891	Guangdong	US-CA, Australia, Canada
April 12	103.6911	Hong Kong	Qatar, Italy, US-CA
	96.0541	Shanghai	Germany, Spain, US-CA
	87.8762	Taiwan	US-CA, US-AL, Germany
	78.3416	Guangdong	Belgium, Qatar, France
	58.6192	Sichuan	England, Israel, Singapore
April 16	351.8334	Shanghai	US-NY, Germany, Italy
	303.8061	Taiwan	US-NY, Canada, Japan
	314.1463	Hong Kong	Singapore, UK, US-IL
	57.1159	Beijing	Germany, Japan, US-CA
	49.4030	Guangdong	France, Canada, Australia

Note: US-NY is New York; US-AL is Alaska; US-CA is California; US-IL is Illinois; US-WA is Washington.

In April, China still faced significant imported case risk from Europe and the US, despite its significant cut of inbound flights. Especially for Beijing and Shanghai, they were still exposed to very high risk of imported cases. This is mainly because mainland China has not cut its flights with Hong Kong. A significant amount of the US and European passengers can still travel to mainland China by transferring from Hong Kong, while Hong Kong did not implement as strict flight cut and inspection policies as adopted in mainland China.

Most of the countries have also adopted stricter international air travel bans and cut the international air connectivity. This indeed helped China to control the imported case risk as well. Fig. 9 depicted the change of international air connectivity for major COVID-19 pandemic countries, namely South Korea, Japan, Singapore, Spain, the US, Italy and Russia. For example, most of the countries cut flights with South Korea and Italy since early March, which decreased the countries' air connectivity dramatically. Spain and the US began to restrict international travels around March 15 and March 20, respectively. On March 15, Spanish Prime Minister Sanchez announced the country lockdown which restricted the international air travel; On March 20, California in the US also locked down, and the Governor of New York also followed up. At the same time, to control imported cases abroad, countries have restricted entry or flights to high-risk areas.

4.4. Imported case risk on major international routes

This subsection focuses on more micro-level risk by examining individual routes between China and foreign countries or different states of the US. First, as shown in Table 6, it is observed that the risk index on each major route was generally low in February. The risk indexes of all the routes were below 10, and there were very fewer reported imported cases in the entire February as well. Those routes with the highest risk mainly concentrate on those nearby Asian countries, linking with Chinese regions such as Hong Kong, Beijing, Taiwan and Shanghai.
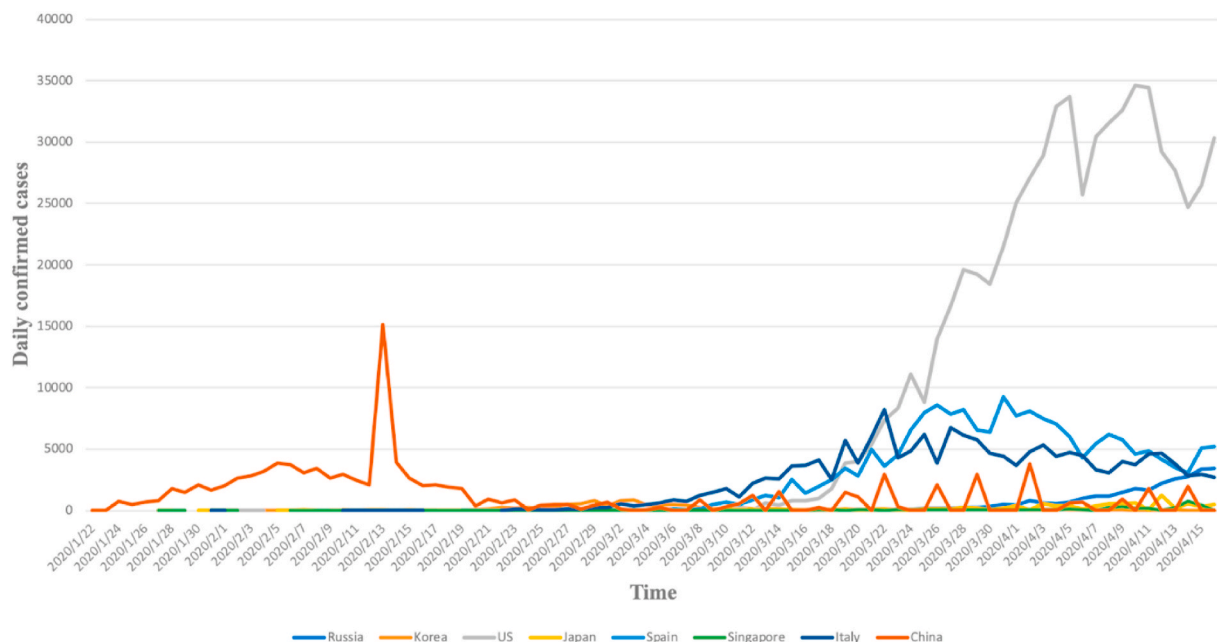

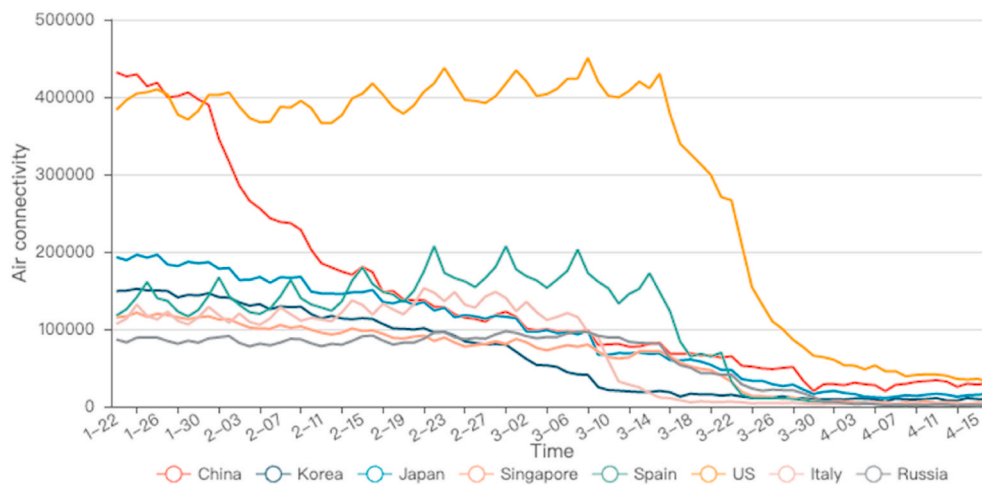**Fig. 8.** Evolution of daily confirmed cases for major countries imposing the risk of imported cases for China.

Fig. 9. Change of international air connectivity for major countries.

Table 6
Route-level risk in February 2020.

Date	February 2			February 12			February 22		
Ranking	Departure	Destination	Risk	Departure	Destination	Risk	Departure	Destination	Risk
1	Singapore	Hong Kong	1.954	Japan	Taipei	4.369	Korea	Taipei	6.524
2	Singapore	Taipei	1.18	Singapore	Hong Kong	3.236	Korea	Hong Kong	3.346
3	Singapore	Shanghai	0.547	Japan	Hong Kong	2.281	Korea	Qingdao	2.178
4	Singapore	Beijing	0.46	Singapore	Taipei	1.99	Japan	Taipei	1.977
5	Australia	Hong Kong	0.271	Japan	Shanghai	1.708	Singapore	Taipei	1.936
6	Korea	Taipei	0.262	Japan	Kaohsiung	0.656	Korea	Kaohsiung	1.673
7	Singapore	Guangzhou	0.245	Japan	Beijing	0.52	Korea	Beijing	1.394
8	Korea	Hong Kong	0.197	Korea	Taipei	0.442	Singapore	Hong Kong	1.111
9	Korea	Shanghai	0.197	Singapore	Shanghai	0.306	Korea	Shanghai	0.836
10	Singapore	Xiamen	0.134	Singapore	Chengdu	0.277	Korea	Pudong	0.836

However, the situation was worsened since March. The overall route-level risk index had increased by 10 times when compared to that of February. With COVID-19 pandemic breaking out in South Korea, the route-level risk between Chinese cities and the South Korean cities increased dramatically. This is clearly shown in that the top-ten riskiest routes on March 2 all involved the South Korean cities, and nine of the top-ten on March 12 were related to South Korea. Since March 22, the routes between Chinese cities and Europe or the US became the riskiest, with the two regions developing into the new pandemic centers. The detailed ranking is shown in Table 7. The top-ranked routes in China not only concentrated in Taipei and Beijing, but also involved some

secondary Chinese airports such as Yanji, Xi'an, and Shenyang. This is because these cities have been designed as the first entry points for the inbound international flights, which were originally scheduled to land in Beijing, Shanghai, and Guangzhou.

Table 8 demonstrated the route-level risk index ranking in April. With the pandemic development in Europe and the US (especially New York), the routes involved in these two regions made up the top-ten the riskiest routes with China. The US-Hong Kong and US-Taiwan routes imposed the highest risk to China. This also explained why Hong Kong and Taiwan kept reporting an increasing number of imported cases in April.

Table 7
Route-level risk in March 2020.

Date	March 2			March 12			March 22		
Ranking	Departure	Destination	Risk	Departure	Destination	Risk	Departure	Destination	Risk
1	Korea	Qingdao	16.473	Korea	Beijing	11.734	US-NY	Taipei	20.852
2	Korea	Shanghai	16.473	Qatar	Hong Kong	8.947	US-NY	Beijing	17.751
3	Korea	Beijing	10.296	Korea	Hong Kong	8.801	US-NY	Tianjin	16.367
4	Korea	Guangzhou	8.442	Korea	Guangzhou	6.16	US-NY	Hong Kong	14.277
5	Korea	Shanghai	6.177	Korea	Shanghai	6.16	Italy	Hong Kong	13.003
6	Korea	Taipei	6.177	Korea	Taipei	5.867	Korea	Shanghai	9.466
7	Korea	Yantai	6.177	Korea	Xi'an	5.867	UK	Hong Kong	7.343
8	Korea	Weihai	5.714	Korea	Tianjin	5.867	Germany	Shanghai	7.139
9	Korea	Tianjin	4.118	Korea	Shenyang	5.867	Germany	Beijing	7.139
10	Korea	Yanji	4.118	Korea	Yantai	5.867	Germany	Taipei	7.139

Note: US-NY is New York.

Table 8
Route-level risk in April 2020.

Date	April 2			April 12			April 16		
Ranking	Departure	Destination	Risk	Departure	Destination	Risk	Departure	Destination	Risk
1	US-NY	Shanghai	102.015	Qatar	Hong Kong	43.574	US-NY	Taipei	233.487
2	US-NY	Beijing	102.015	Germany	Shanghai	43.366	US-NY	Shanghai	233.487
3	Germany	Shanghai	34.173	Spanish	Shanghai	38.747	Germany	Shanghai	48.835
4	UK	Hong Kong	31.698	Belgium	Guangzhou	37.418	US-CA	Taipei	43.018
5	UK	Taipei	21.132	US-CA	Taipei	36.403	US-IL	Hongkong	41.987
6	US-WA	Taipei	19.861	Italy	Hongkong	34.942	US-IL	Taipei	41.987
7	Germany	Beijing	17.087	US-AK	Hongkong	31.764	Italy	Shanghai	35.74
8	France	Tianjin	13.617	US-CA	Shanghai	24.269	Italy	Wenzhou	35.74
9	France	Taipei	13.617	US-CA	Hongkong	24.269	Singapore	Shanghai	32.44
10	Netherlands	Hongkong	13.486	US-AK	Taipei	23.823	Canada	Taipei	32.44

Note: US-NY is New York; US-AL is Alaska; US-CA is California; US-IL is Illinois.

Such a route-level risk index is more useful for the relevant stakeholders to adjust international air travel restrictions, which can be specific to an individual Chinese airport and a particular foreign country. Because our proposed approach is based on the real-time data, the risk index can be calculated and updated day by day. It would help policy makers, airlines, customs, border inspections, epidemic prevention departments and the hospitals to prepare in advance. It is useful to judge whether the future flight plan can be adjusted according to different risk levels. This provides a theoretical and quantitative basis for timely flight plan adjustment. Especially, for the low-risk routes, the air travel ban can be lifted to resume the normal operation as soon as possible. This is important to mitigate the negative economic and social impact of the COVID-19 pandemic.

5. Conclusion

International air travel has contributed to the global spread of COVID-19. Although many countries have controlled local pandemic or seen the curve of newly reported cases flattened, there has been no sign for the virus to disappear in the near future. Given the fast spread of COVID-19 around the world, it is still essential and even urgent for each country to stipulate effective measures to control the imported case risk from inbound international flights. A too soon relaxation of international air travel restriction is likely to result in new imported cases from overseas and lead to local pandemic revival. Moreover, it is necessary to accurately measure the imported case risk of inbound flights from different foreign countries and even specific routes. This is useful to tailor the restriction rule based on different risk levels. This helps mitigate the imported case risk, while minimizing the impact on the essential international air travels.

This paper proposed a risk index to measure the risk of imported cases by inbound international flights. The index combines both international air connectivity and COVID-19 pandemic data. The method was applied to calculate risk index for each province in China. With the COVID-19 pandemic first emerged in Wuhan in January 2020, China has adopted a series of powerful measures, including the lockdown of Wuhan and other cities. It has been the first country to effectively contain the pandemic and reopen the domestic economy. However, the country was then exposed to very high risk of imported cases, when COVID-19 quickly spread globally.

Our calculated risk indexes for China have shown clear spatial and temporal patterns. First, there is clear evidence that China's inbound flight restriction since late March has been quite effective to control the imported case risk. The counterfactual analysis showed that the overall risk index level has been reduced by half thanks to the strict restriction. Second, China's imported case risk has kept growing from January to

April, despite the cut of international air connectivity by China and many other countries. This is mainly because COVID-19 was spreading extremely fast around the world, which dominated the air connectivity reduction and thus raised China's imported case risk. This thus calls for continuous caution for policy makers to restrict international air travel from high risk regions. Third, in February and early March, South Korea and some other Asian countries imposed higher imported case risk to China. Later, Europe and the US became the pandemic centers since mid-March. This made China to face more imported case risk from the inbound flights from these two regions. Fourth, it is noted that Hong Kong did not strictly restrict its international air connectivity, while mainland China has still kept most of the flights with Hong Kong. This thus indirectly made mainland China exposed to higher imported case risk from those overseas passengers who can transfer from Hong Kong to enter mainland China. Last, we also examined the risk index for each province and identified the major foreign countries that imposed high risk. Some route-level risk indexes have also been scrutinized. The proposed index can provide useful references for policy makers, airlines and other relevant stakeholders to adjust the international air travel restrictions in advance.

This study, however, is also subject to some limitations, which open avenues for future studies. First, although, for the US, we distinguish the imported case risk from different US states, for other large countries, such as US and Russia, we are not able to examine the risk at the province level. This is simply because of the data unavailability. But the research method and framework can be directly applied to measure the province-specific imported case risk for these countries, once more micro-level data become available. Second, as most of the connecting flights and transfer passengers have been banned for international air service, our imported case risk now only accounts for the direct international flights. When the restrictions are gradually lifted, the connecting flights would rebound and transfer passengers are allowed to travel, the existing method can be easily adapted to account for the imported case risk of the connecting flights. As long as having the detailed itinerary information of the passengers or at least knowing the share of origin and transfer passengers per flight, we should be able to distinguish how much the imported case risk from the origin and intermediate countries of the particular flight. These are all very meaningful extensions with valuable policy implications in the near future, but are out of the scope of this paper.

Author's statement

All the co-authors declare that we do not have any copyright issue with this paper. The paper has not been submitted or published in other journals. We also do not see any conflict of interest involved in this

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